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THE EFFECT OF ENERGY-EFFICIENT LIGHT SOURCES ON THE QUALITY OF ELECTRICITY

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Abstract

The paper analyzes the range of current from energy-efficient light sources (LSs), such as compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs). The studied LSs exceed the standard values for the current harmonics, even with passive power factor correction.

We have developed a methodology for calculating relative errors of active energy meters that measure the energy used by CFLs and LEDs and applied the methodology to determine the values of the relative errors of the induction and the digital meters. It is found that the errors of of both types of electricity meters for measuring power in the circuits with the tested LSs–CFLs and LEDs–exceed the maximum permissible errors by 3.0 % and 4.0 % respectively. Thus, when the load is a source of non-sinusoidal current, a consumer is overcharged for electricity.

The values of errors in electricity metering can be reduced by eliminating the causes of the deteriorating quality of electricity, i.e. by supplying the lighting installations with energy-efficient light sources provided with active power factor correction.

Keywords: energy efficiency, electricity, power, spectrum/range of current, active energy meter.

1. Introduction

The volume of electricity used by a lighting installation (LI) depends on its energy efficiency. The introduction of energy-efficient light sources, such as compact fluorescent lamps and light-emitting diodes, can increase the energy efficiency of lighting installations, and thus reduce the cost of electricity.

CFLs and LEDs are powered by built-in secondary sources of power supply that form a nonlinear load and a source of a higher-harmonic current. Active electrical energy meters are required the following: (1) the content of a higher-harmonic voltage should not exceed 1 % and (2) the amplitude of the higher-harmonic current should not exceed 10 % of the amplitude of the fundamental harmonics [1]. Obviously, an error of the meter affected by non-sinusoidal currents and voltages differs from the permissible one. The above factors testify to the importance of studies how energy-efficient light sources affect the values of electricity quality and its metering errors.

The purpose of the research is studying the effect of energy-efficient light sources on the quality of electricity and its metering.

Setting objectives. Measuring the range of power supply in energy-efficient light sources. Working out a methodology for calculating the relative errors of meters that measure the electric power used by CFLs and LEDs. Analyzing the impact of the harmonic currents of power supply in energy-efficient LSs on the error values.

2. Materials and methods

One study of the problem [2] presents an experimental finding of the error of a single-phase induction-type energy meter by alternating the voltage in the range of ± 20 % of the nominal voltage and varying the current 10 % to 300 % of the nominal current when the power factor values are 0.8, 0.9, and 1.0. The above study proves that the effect of the power factor on the errors of meters is not clearly expressed, but the *PF* growth leads to the error reduction.

Another study [3] assesses the accuracy of measuring the electricity consumption of a LED light source. The researchers used a digital multi-tariff meter as a power measuring device and found that the relative meter error δ depends on the relative content of higher harmonics.

The above dependence is described as the function:

$$\delta = f\left(\frac{P_k}{P_1}, k = 2,3,...\right), \quad (1)$$

where P_1 and P_k denote the first and the k harmonic voltages.

The next study [4] focuses on functioning of the same-type meters in the same conditions. The testing used the meters as an output parameter and accounted for errors in the measurements of active energy per units of time or power. The research used alternating parameters in the following ranges:

– the power factor–0.1 %...1.0 %,
– the voltage deviation– -10 %...+40 %,
– the coefficient of distortion for current and voltage waveforms–0 %...25 %,
– the coefficient of harmonic components for odd harmonics–0 %...12 %, and
– the coefficient of harmonic components for even harmonics–0 %...12 %.

The meter tests show that the active energy measurement error significantly increases when the electricity quality and the power factor decrease.

One more research [5] revealed that the 17th and higher harmonics with the values ≥ 5 %...7 % caused some electricity meters completely come out of order and show the readings that were several times different from the actual values of the electrical power. The error can reach 10 %...20 % (according to the findings of the Fluke company-up to 68 % [6]).

Study [7] considers the problem of reliability of metering electricity in outdoor lighting installations with nonlinear loads. It was found that the effect of non-sinusoidality on the total error of induction-type meters is most evident at the frequencies of the 11th and the 13th harmonics. The researchers proposed installing modern electronic power factor correction that would significantly reduce the metering error and improve electricity metering in the systems for street lighting.

Thus, the accuracy of meter readings greatly depends on the quality of the measured energy. The fact that CFLs and LEDs are sources of higher harmonics makes studying the effect of electrical parameters of energy-efficient light sources important.

3. Experimental procedures

3. 1. Measuring current and voltage waveforms in CFLs and LEDs

The paper presents measurements of current and voltage waveforms in CFLs (Realux 55W, Maxsus 55W, Global 46W, and Realux 36W) and a LED (Philips 14W LED). This becomes possible owing to the designed installation whose flowchart is shown in **Fig. 1**.

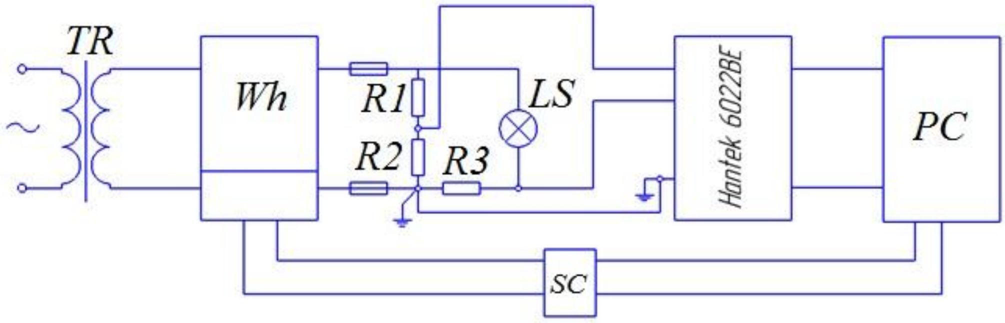


Fig. 1. A flowchart of the installation for measuring the waveforms of current, voltage and power of energy-efficient light sources

Current and voltage waveforms were measured with the help of a voltage divider–R1 and R2–and a shunt–R3–with a USB oscillograph Hantek 6022BE. Resistors with a low temperature coefficient were selected to reduce the effect of temperature on the electrical resistance of R1, R2, and R3. The resistance was measured with the bridge P-369 that allows an error ≤ 1 %. The Fourier analysis of the current waveforms was provided with a program specially developed in the Matlab.

3. 2 Measuring the relative error of the meters of active electrical energy used by CFLs and LEDs

The relative error δ of the meter is calculated as follows [2]:

$$\delta = \frac{W - W_0}{W_0} \cdot 100\%, \quad (2)$$

where W is electric power according to the readings of the tested meter, and

W_0 is electric power according to the readings of the sample meter.

The electric power was measured with the induction-type meter *Rostok SO-5000* and the electronic meter *Meridian SOE-1.02/5KRTD.*

Formula (2) allows writing an expression for calculating relative errors of the induction-type δ_i and the electronic δ_e meters respectively:

$$\delta_i = \frac{W_i - W_0}{W_0} \cdot 100\%, \quad (3)$$

$$\delta_e = \frac{W_e - W_0}{W_0} \cdot 100\%, \quad (4)$$

where W_i is electric power according to the readings of the induction meter, and

W_e is electric power according to the readings of the electronic meter.

W_i and W_e were calculated due to the meter parameters C_i and C_e that show the number of dial rotations in the induction meter and the number of the "metering" LED flashes in the electronic meter that correspond to the consumption of 1 kWh of electrical energy. The induction meter *Rostok SO-5000* has $C_i = 250$ r/kWh. The electrical energy value w_i (measured with the above meter) per one dial rotation is calculated as follows:

$$w_i = \frac{3,6 \cdot 10^6}{250} = 14400 \text{ (Ws)}. \quad (5)$$

The electrical energy consumed within the interval of n dial rotations is calculated as:

$$W_i = w_i n = 14400n \text{ (Ws)}. \quad (6)$$

The electronic meter *Meridian SOE-1.02/5KRTD* has $C_e = 3200$ imp/kWh. Thus, within the interval between flashes Δt the load consumes energy w_e calculated as:

$$w_e = \frac{3,6 \cdot 10^6}{3200} = 1125 \text{ (Ws)}. \quad (7)$$

The number of the "metering" LED flashes N in the electronic meter was registered by the personal computer (PC) aided by the signal conditioning device (SC). The electrical energy consumed within the interval of N flashes of the "metering" LED is calculated as:

$$W_e = w_e\left(N-1\right) = 1125\left(N-1\right) \text{ (Ws)}. \quad (8)$$

W_0 was found from the current and voltage waveforms of the tested LSs as follows:

$$W_0 = P_0 t\,. \quad (9)$$

The loading power P_0 of the tested LSs was measured at the designed installation (**Fig. 1**). The light source (LS) is powered from the electricity grid of a variable voltage 220W via the transformer (TR) that serves as a galvanic isolator between the grid and the light source (LS). The meter (Wh) and the light source (LS) were connected in the secondary winding of the transformer. The power P_0 was calculated with avoidance of the effect of instable parameters in the grid. Thus, the waveforms were recorded with the interval of 10 seconds during the testing time t. The power P_{0j} for the j testing was calculated by the following formula:

$$P_{0j} = U_{1j} I_{1j} \cos\left(\varphi_{1j}\right), \quad (10)$$

where φ_{1j} is the angle of the phase slide between the actual voltage U_{1j} and the first-harmonic current I_{1j} for the j testing respectively. Their values are calculated as follows:

$$U_{1j} = \frac{U_{1m}}{\sqrt{2}}, \quad (11)$$

$$I_{1j} = \frac{I_{1m}}{\sqrt{2}}. \quad (12)$$

The power P_0 was calculated by the following formula:

$$P_0 = \frac{\sum_j P_{0j}}{j}. \quad (13)$$

Accounting for the above equations (10)-(13), the power factor (PF) was calculated as follows:

$$PF = \frac{P_0}{S} = \frac{I_{1m}\cos\varphi_1}{\sqrt{I_{1m}^2 + I_{3m}^2 + I_{5m}^2 + ... + I_{km}^2}} = K_{ND}\cos\varphi_1 = \frac{\cos\varphi_1}{\sqrt{1+K_H^2}}, \quad (14)$$

where I_{km} is the amplitude of the k-harmonic current,

K_{ND} is the coefficient of nonlinear distortions of the electric current, and

K_H is the coefficient of the harmonic current.

The methodology of calculating the relative error of the active energy meters includes metering the electrical energy used by CFLs and LEDs and consists of the following steps:

(1) metering the number of disc rotations n for the induction meter and the number of the LED flashes N for the electronic meter during the testing time t when they are loaded with the tested LSs,

(2) recording the LS current and voltage waveforms within the testing time t with the interval of 10 seconds and calculating P_{0j} by formula (10),

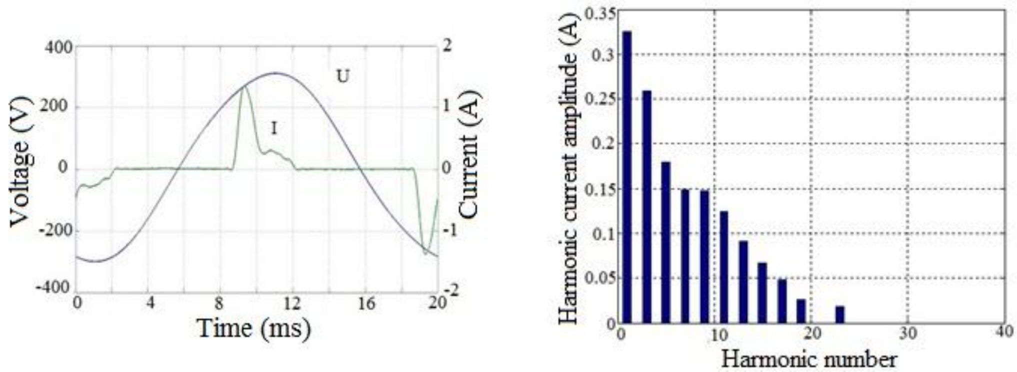
(3) calculating power P_0 by formula (13),

(4) calculating the consumed electrical energy W_i, W_e and W_0 by formulae (6), (8), and (9), as well as

(5) calculating the relative errors δ_i and δ_e of the induction and the electronic meters, respectively, by formulae (3) and (4).

4. The research findings and their discussion

Fig. 2 shows current and voltage waveforms as well as current harmonics (in the right column) for the tested LSs.



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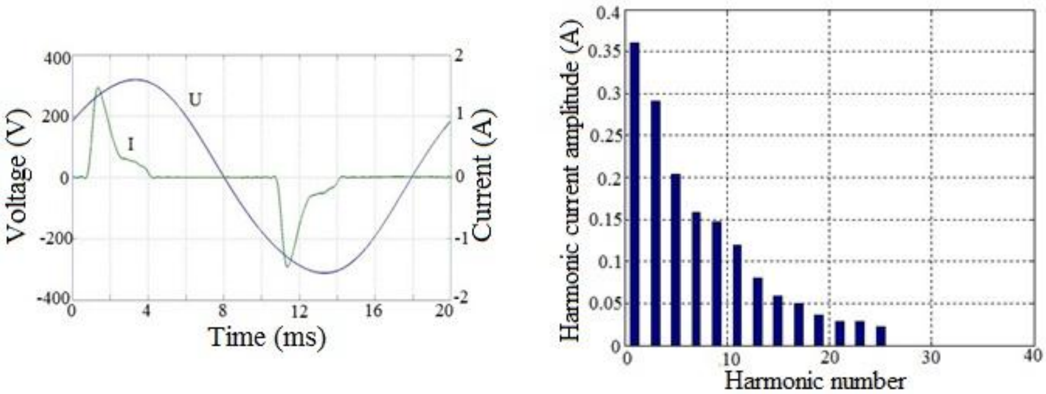

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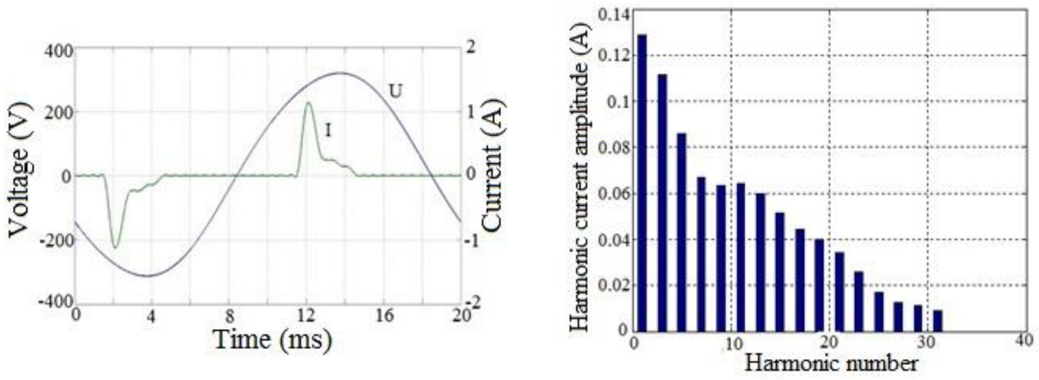
Fig. 2 (a– b). Current and voltage waveforms and current harmonics for the lamps:
a – Realux 55W;b – Maxsus 55W



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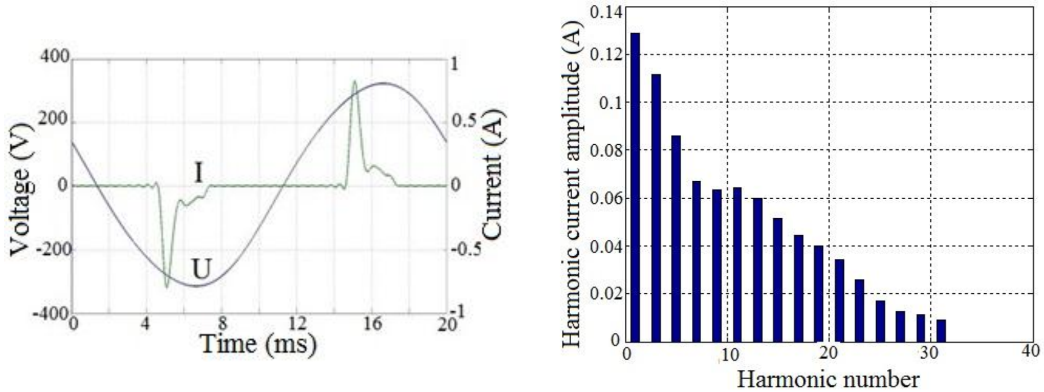

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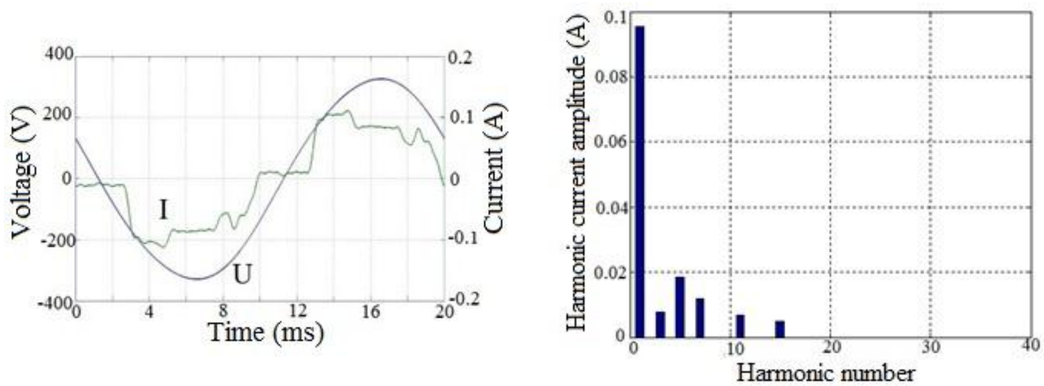


e

Fig. 2 (c – e). Current and voltage waveforms and current harmonics for the lamps:
c – Global 46W;d – Realux 36W;
e – Philips 14W LED

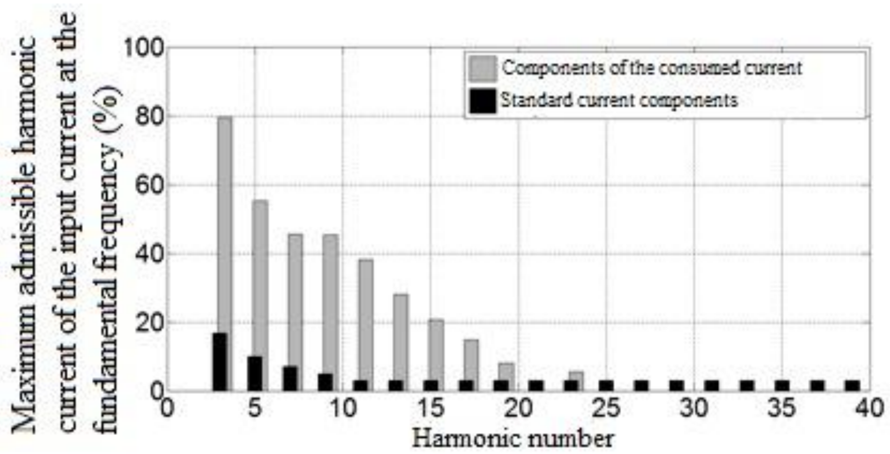
We have made a comparative analysis of the compliance of the current harmonics of the tested LSs with the DSTU IEC 61000-3-2:2004 [8] and the EN 61000-3-2:2006 [9] standards (**Table 1**). For LSs ≤ 25W the values are shown as current values per unit of the consumed power, whereas for LSs > 25W—as % of the amplitude of current at the fundamental frequency.

Table 1
Limit values of the harmonic components in the consumed current for the lighting installation under the DSTU IEC 61000-3-2:2004 and the EN 61000-3-2:2006 standards

Harmonic order		2	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39
Power	≤25W		3.4	1.9	1.0	0.5	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1		0.1	0.1	0.1	0.1	0.1
	>25W	2	30·PF*	10	7	5	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Note. * *PF* is a power factor

Fig. 3 shows a harmonic content of the consumed current in comparison with the standard data for the tested LSs.



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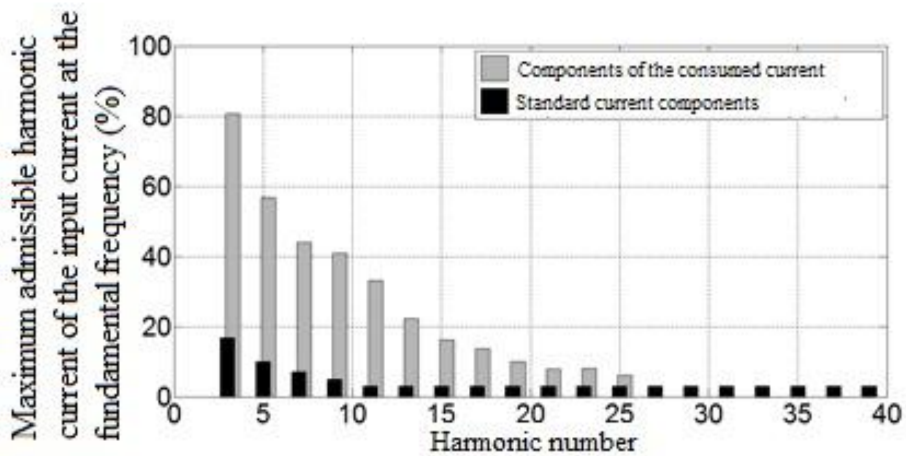

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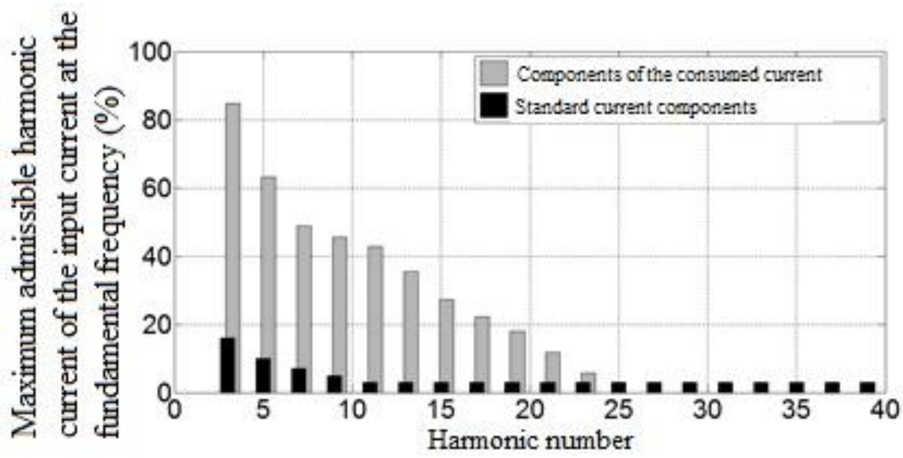
Fig. 3 (a – b). Harmonic content of the consumed current in comparison with the standard data for the lamps: a – Realux 55W; b – Maxsus 55W



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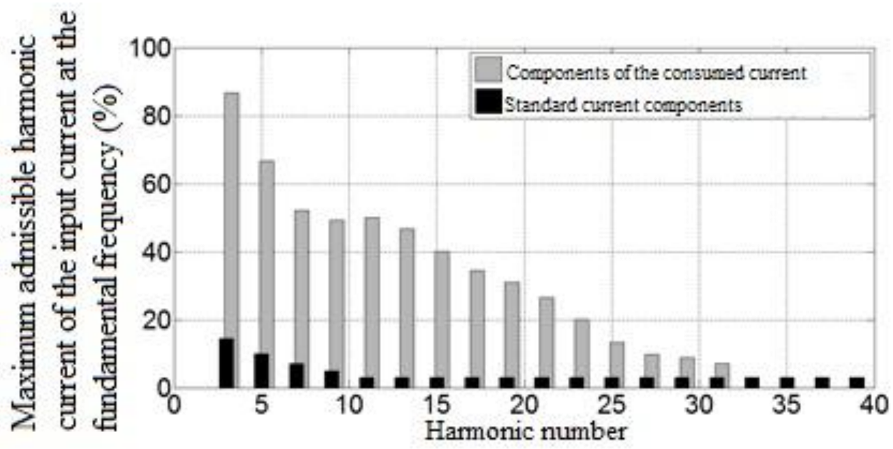

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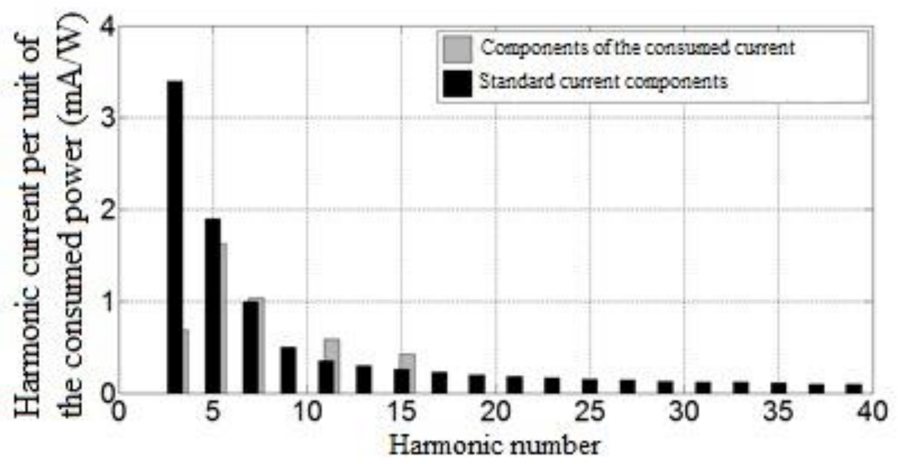


e

Fig. 3 (c – e). Harmonic content of the consumed current in comparison with the standard data for the lamps:
c – Global 46W; d – Realux 36W;e – Philips 14W LED

Fig. 3 shows that harmonic content of the current used by the tested CFLs exceeds the standard data. In lamps 46W and 55W, harmonics higher than 25th conform to the standard data, whereas in the lamp Realux 36W the compliance is observed after the 29th harmonics. The LED lamp Philips 14W LED does not comply with the standard data for the 7th, 11th and 15th harmonics.

The calculated values of the relative errors δ_i and δ_e of the meters and the calculated PF coefficients are shown in **Table 2**.

Table 2
Relative errors of Rostok SO-5000 and Meridian SOE-1.02/5KRTD that meter the electricity used by the tested CFLs and LEDs

Light source (LS)	PF	δ_i (%)	δ_e (%)
Realux 55W	0.3442	8.01	6.07
Maxsus 55W	0.3514	7.97	5.13
Global 46W	0.3067	8.55	5.75
Realux 36W	0.249	17.7	6.18
Philips 14W LED	0.893	12.51	4.48

According to the passport data [10], *Rostok SO-5000* has a maximum permissible error of 2.5 % if the current value is 5.0 % of the nominal one $(I_{nom} = 10A)$. The highest error value for CFLs–17.7 %–occurs with the lamp Realux 36W, which is caused by the high values of the higher harmonic current.

The electronic meter *Meridian SOE-1.02/5KRTD* has an electricity metering error that varies from 4.0 % to 8.0 %, whereas the permissible error is 1.0 % with a minimum sensitivity of 20 mA [11]. Similarly to the induction-type meter, the electronic meter has a maximum error for CFLs–6.18 %–with the lamp Realux 36W. It should be noted that increasing power factor results in lower errors of the tested meters.

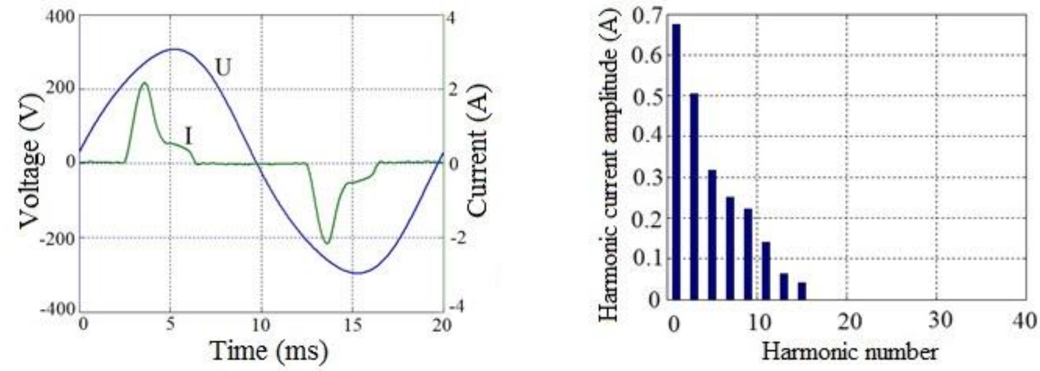
One of the reasons that leads to high error rates of the meters is low values of the lamp operating current. The meters were tested for errors by means of several simultaneously incorporated lamps that increased the current values. The obtained results are shown in **Fig. 4**.

When two or more lamps are connected in a circuit, the amplitude values of higher harmonics tend to decline. **Table 3** shows the relative errors of the meters of electricity consumption in the circuits that incorporate several operating lamps.

Table 3
Relative errors of Rostok SO-5000 and Meridian SOE-1.02/5KRTD that meter the electrical energy used by several incorporated CFLs

Light source (LS)	PF	δ_i (%)	δ_e (%)
Maxsus 55W and Realux 55W	0.4339	5.45	5.09
Maxsus 55W, Realux 55W, and Realux 36W	0.4634	4.91	4.72
Maxsus 55W, Realux 55W, Realux 36W, and Global 46W	0.5162	4.25	4.53

As can be seen from **Table 2**, the error of the electronic meter *Meridian SOE-1.02/5KRTD* is on average 2.5 times lower than the error of the induction meter *Rostok SO-5000*. However, when the amperage increases (when several LSs are incorporated simultaneously), the errors of the tested meters are almost identical (**Table 3**). Thus, we can conclude that the high value of the induction meter error in the first case is caused by the low operating current of the lamp. Nevertheless, the errors of both meters remain higher than the permissible one.



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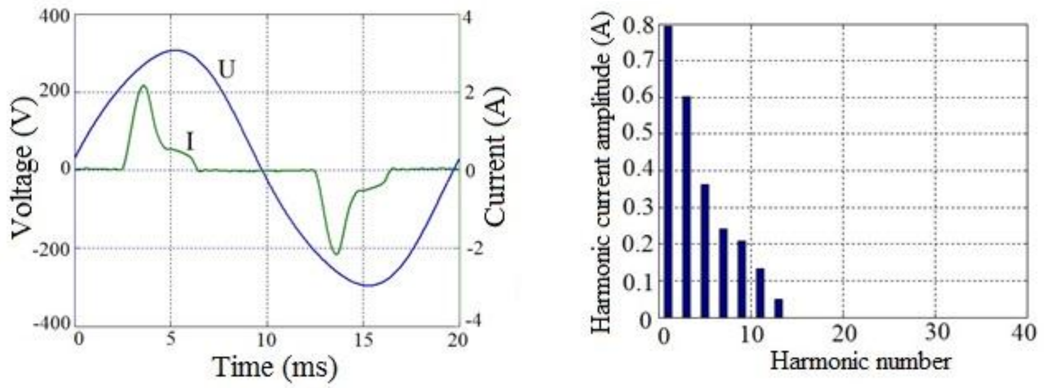

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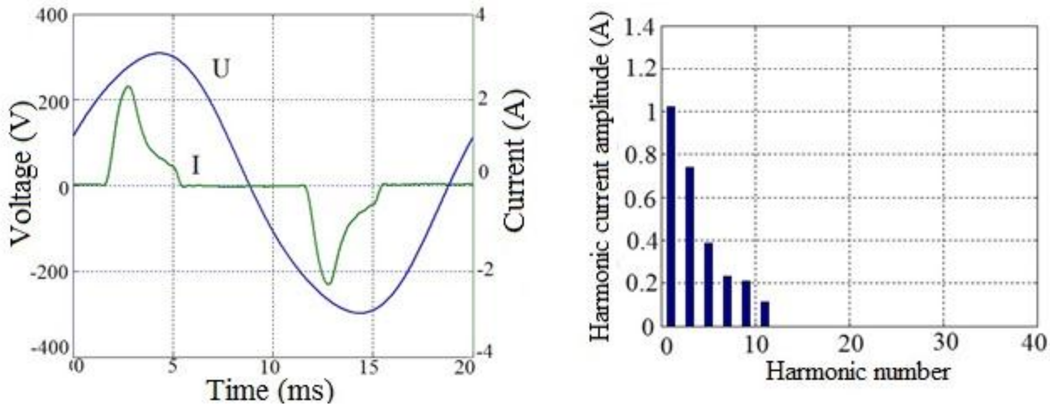

c

Fig. 4. Current and voltage waveforms and current harmonics for the lamps: a–Realux 36W and Global 46W; b–Realux 36W, Global 46W, andMaxsus 55W; c–Realux 36W, Global 46W, Maxsus 55W, and Realux 55W

5. Conclusion

The paper analyzes the current range of energy-efficient light sources, such as CFLs (Realux 55W, Maxsus 55W, Global 46W, and Realux 36W) and a LED (Philips 14W LED). It is found that the tested CFLs exceed the standard indices of the current harmonics, even with a passive power factor correction. In the lamps of 46W and 55W harmonics higher than 25th conform to the standard data, whereas in the lamp Realux 36W the compliance is observed after the 29th harmonics. The LED lamp Philips 14W LED does not comply with the standard data for the 7th, 11th and 15th harmonics.

The developed methodology was used to calculate the values of the relative errors of induction and electronic meters when they measure electricity consumption of CFLs and LEDs.

The analysis shows how the current harmonics of the tested light sources affects the value of error in electricity metering. It is found that the errors of the induction meter *Rostok SO-5000* and the electronic meter *Meridian SOE-1.02/5KRTD* used for metering electricity in the circuits with CFLs and LEDs exceed the maximum permissible errors by 3.0 % and 4.0 % respectively. Thus, when the load is a source of non-sinusoidal current, the consumer is overcharged for electricity.

The errors of electricity metering can be reduced by eliminating the causes of deterioration in the quality of electricity, i.e. by using energy-efficient light sources with active power factor correction in lighting installations.

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